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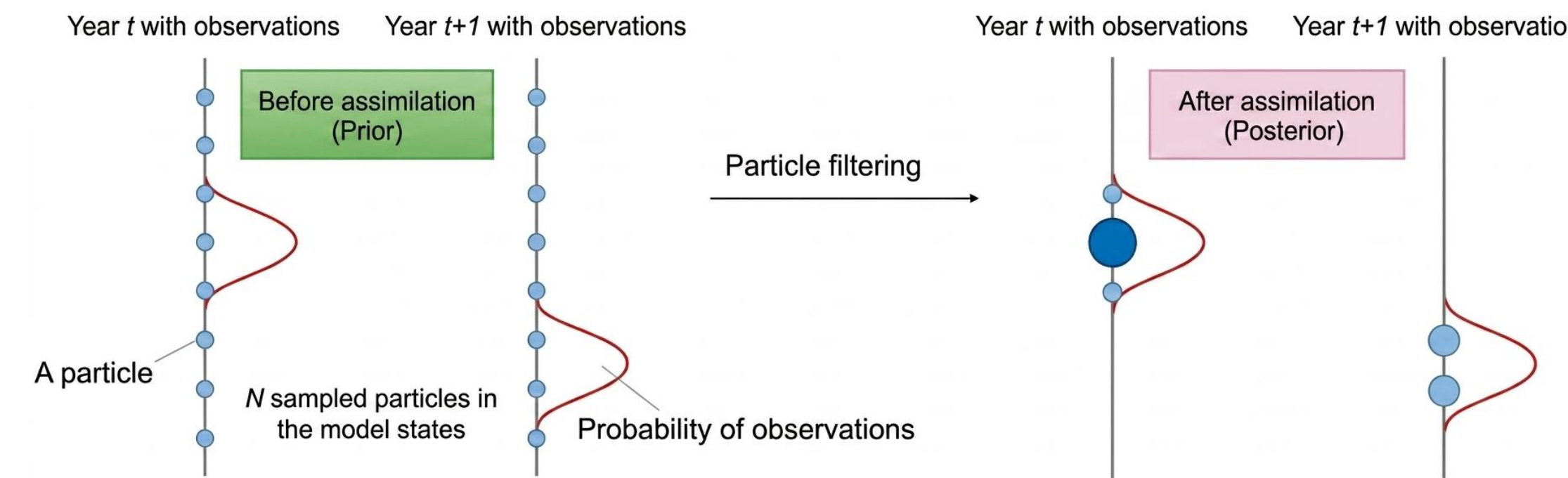
## Background:

- Ongoing drying in Europe and the need for long-term historical context
- Challenges in understanding European summer drought dynamics

## Goals:

- Reconstruct physically coherent European hydroclimate changes over the last millennium
- Identify physical mechanisms underlying summer drought variability and trends from a past-millennium perspective

## Methods: Paleoclimate data assimilation (offline Particle filtering)



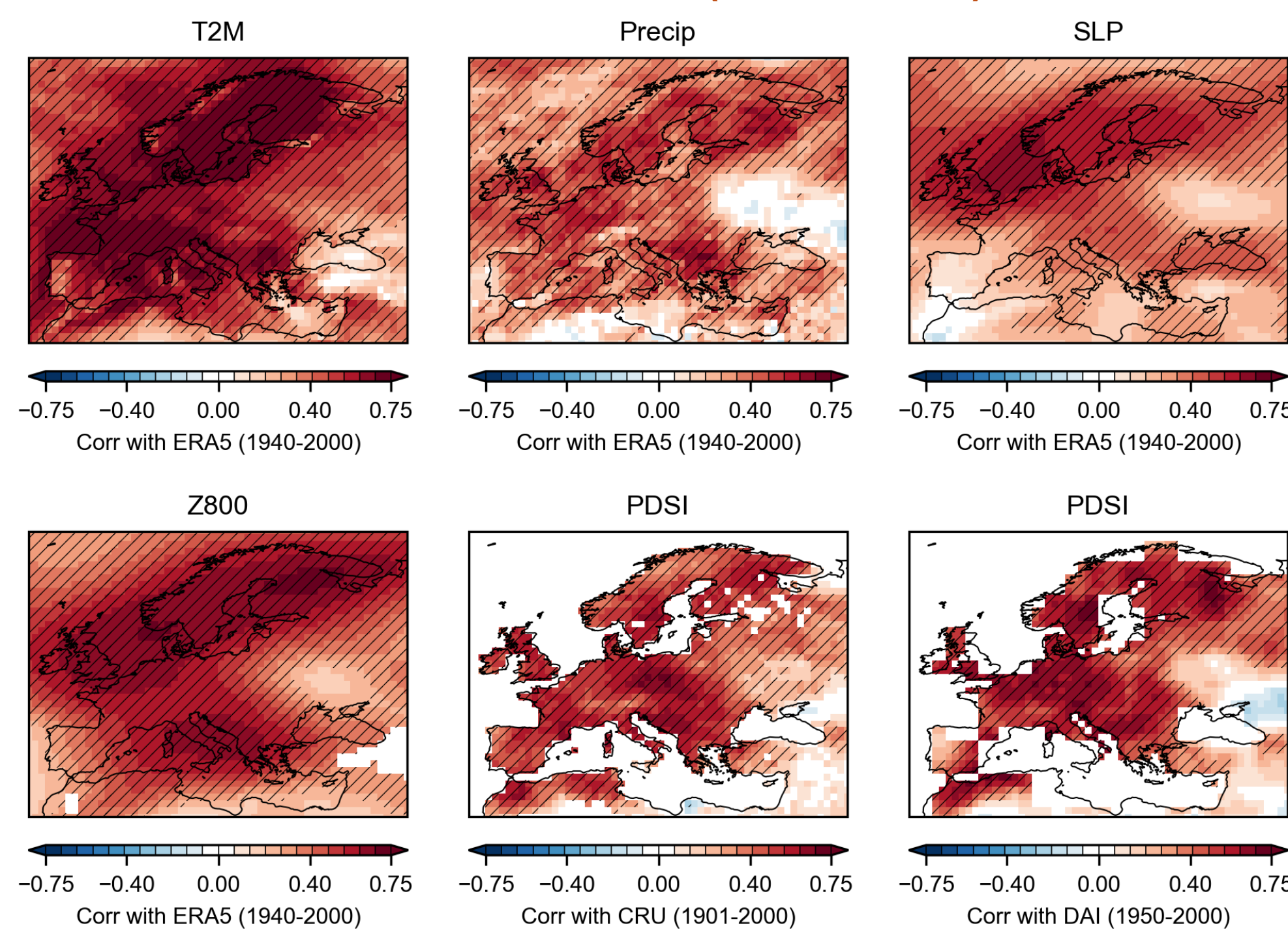
## Proxy System Models

- Three seasonal windows: (i) annual, (ii) JJA, or (iii) MAMJJAS
- Two types of regression modes: univariate or bivariate

## Earth System Model simulations

- CESM1-LME (12)
- ACCESS-ESM1-5 (1)
- MIROC-ES2L (1)
- MRI-ESM2-0 (1)
- CESM2-LE (100)

## 1 European Last Millennial Data Assimilation (EULMDA)



SLP: sea-level pressure; Z800: Geopotential height at 800hPa; PDSI: Palmer Drought Severity Index;

### Summer large-scale circulation modes are well captured:

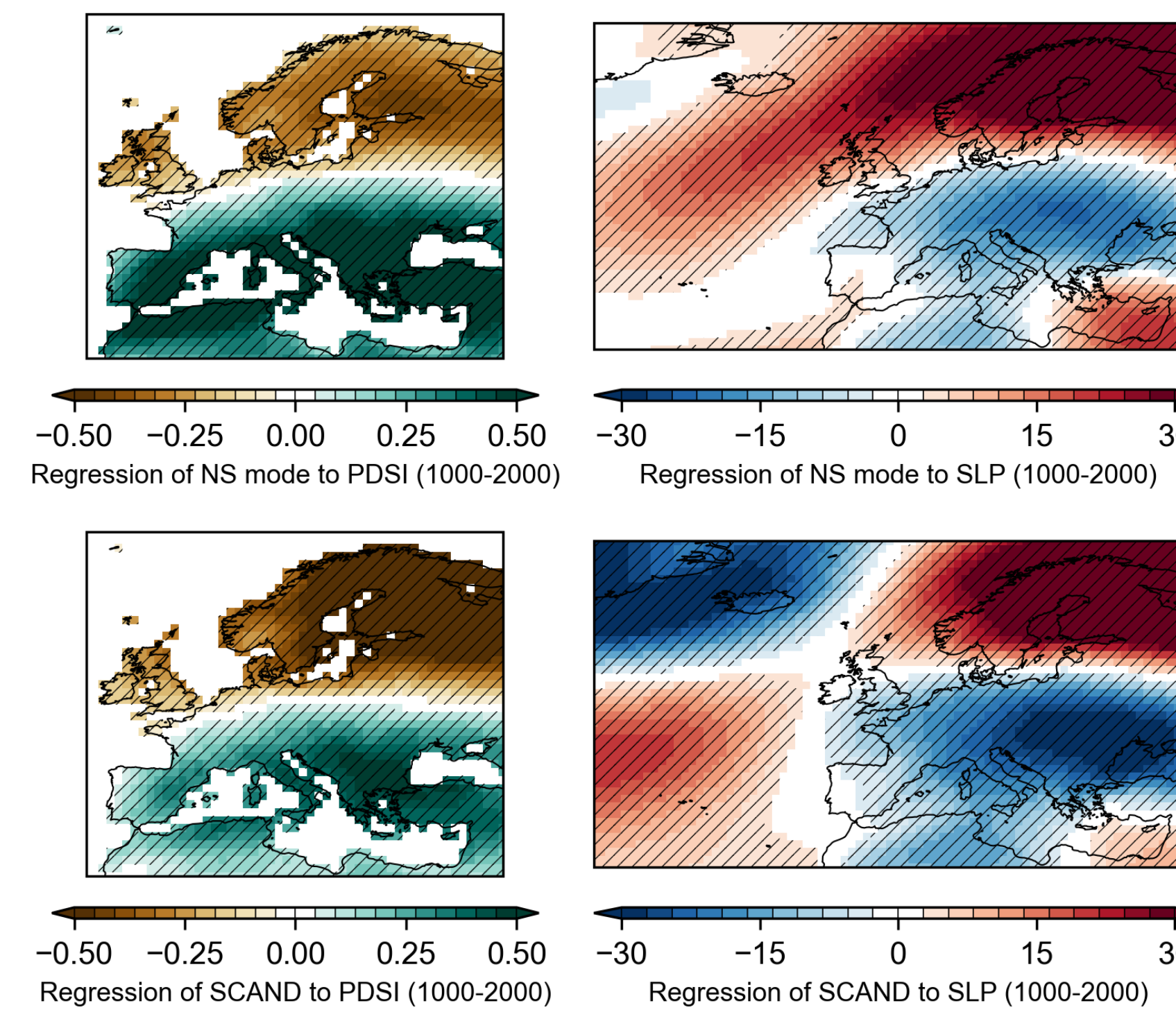
- $r = 0.5^*$  for JJA North Atlantic Oscillation (NAO)
- $r = 0.7^*$  for JJA European-sector Scandinavian pattern (SCAND)

### Independent validation using early instrumental measurements and documentary evidence:

- Significant correlations with Alpine temperature and precipitation reconstructions (Casty, C. et al. 2005)
- $r = 0.42^*$  with Paris precipitation over 1700–2000 CE (Slonosky et al., 2022)

**Reference:** Xue, H., Goosse, H., Dalaiden, Q. et al. *Scandinavian pattern and temperature changes shape European summer droughts over the past millennium*. Nature Communications, accepted.

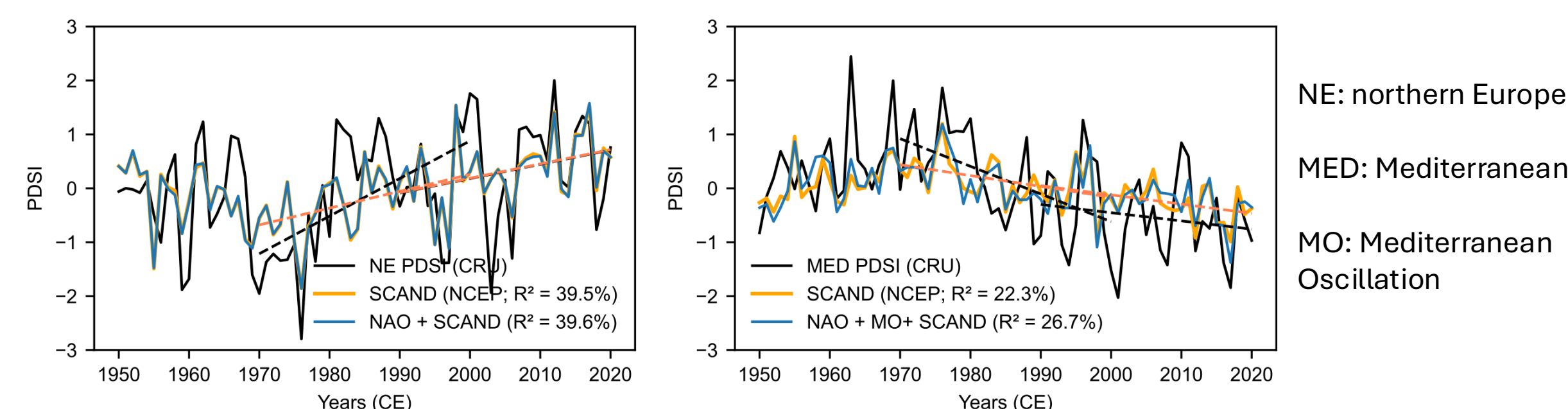
## 2 North-south dipole drought pattern and its drivers



North-south dipole pattern (NS mode): the **first** EOF mode of EULMDA PDSI over 1000–2000 CE (42.8%)

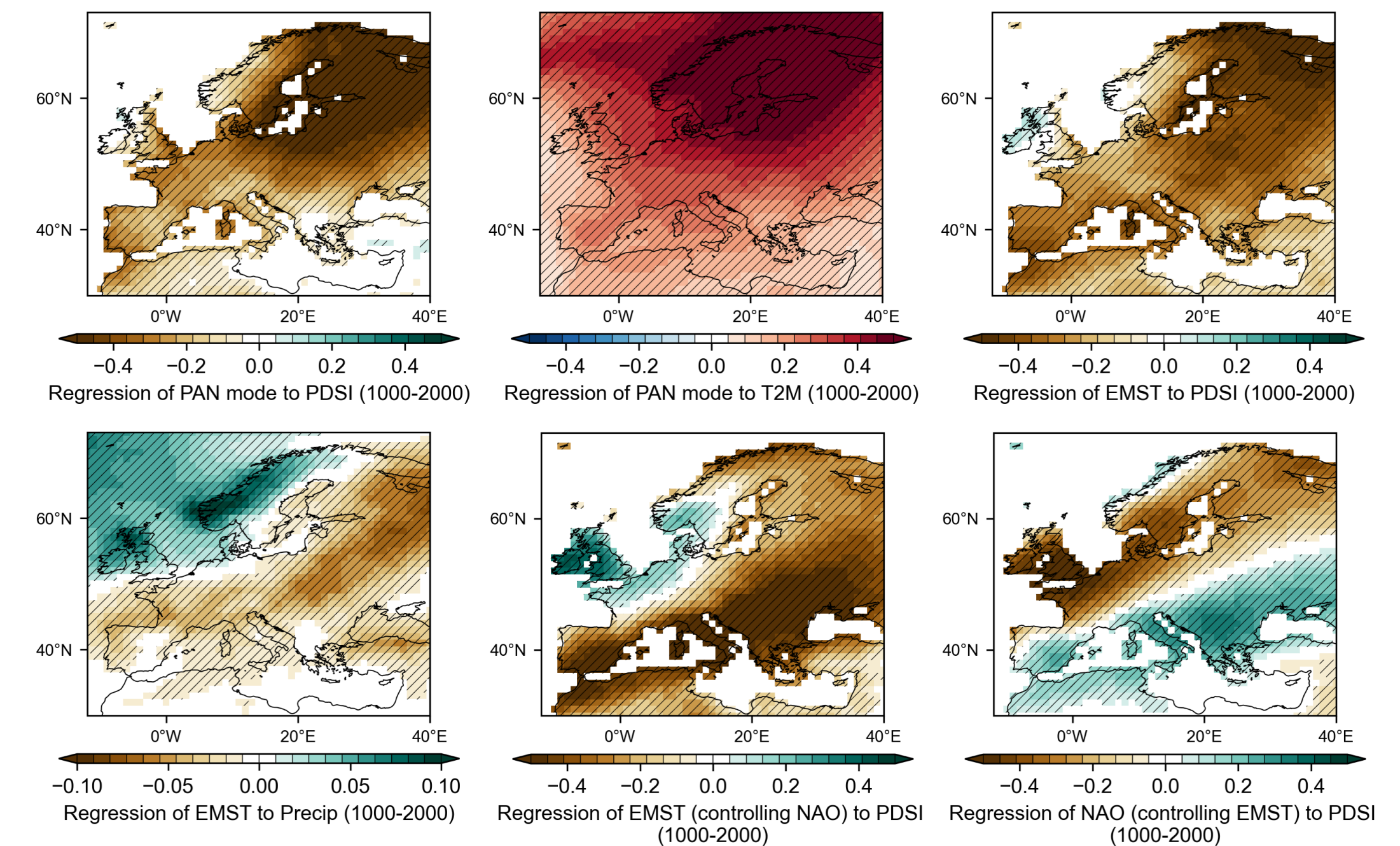
$r = 0.78^*$  between SCAND and NS mode

$r = -0.90^*$  for SCAND and Northern European PDSI and  $r = 0.53^*$  for the Mediterranean PDSI



- The reconstruction-based relationships are also evident in the instrument-based data
- SCAND is a key driver of Mediterranean summer hydroclimate, explaining more variance in precipitation and PDSI than NAO + MO during 1950–2020 CE

## 3 Pan-European drought pattern and its drivers



Pan-European pattern (PAN mode): the **second** EOF mode of EULMDA summer PDSI over 1000–2000 CE (24.8%)

- European mean surface temperature (EMST) explains 44% of PAN mode variance
- Summer NAO covaries with EMST ( $r=0.78^*$ )  $\xrightarrow{\text{Removing EMST}}$  explaining 20% of variance

## Key takeaways

- European summer drought variability is shaped by two main drivers: a dynamically driven north-south dipole linked to SCAND, and thermodynamically driven pan-European mode associated with summer warming.
- Improving the representation of SCAND variability and its interaction with warming will be critical for reliable near-term drought predictions and long-term risk assessments for Europe.